LCA Methodology

Allocation for Cascade Recycling System

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Abstract

Allocation in LCA is defined as partitioning the responsibility for environmental burdens from the economic activities to a reference flow or a reference life cycle system in some proper shares. The result of LCA study involving a multi-input/output system or an open loop recycling system is affected significantly by the choice of the allocation method. For the case of allocation in a cascade recycling system, the quality of material as well as the material flow should be considered. Therefore, environmental burdens from the primary material production, the recycling process and the waste management process have to be allocated in proportion to the quality degradation of a material and to the quantity of a material used in each life cycle system. This paper proposes an allocation method for the cascade recycling system that considers both quality and quantity of a material used.

Keywords: Allocation in LCA; allocation, cascade recycling system; cascade recycling system, allocation; environmental burdens, allocation; LCA; Life Cycle Assessment (LCA); material production, allocation; material quality and quantity, allocation method; open loop recycling, allocation; quality degradation, allocation; recycling process, allocation; waste management process, allocation

1 Introduction

The choice of an allocation rule is important in LCA and influences the results of the LCA. The allocation rule decides how to allocate environmental burdens in a multi-input/output system or in an open loop recycling system. The portion of the environmental burden allocated should follow the causality for these systems. In a multi-input/output process, the environmental burden from the process itself are allocated to a reference flow. For open loop recycling, the environmental burdens from a raw material production process and a waste management process in other life cycle systems, as well as a recycling process, are allocated.

An open loop recycling system where **quality degradation** occurs is called a cascade recycling system. When material is used or recycled over and over again its quality becomes too low to be used any further as a raw material in another life cycle system. The quality degradation is therefore one of the main reasons for the material's disposal. Another possible reason for the disposal is an **economic aspect** of the recycled material. If there is no economic value, the recycled material is no longer used and is diverted into to the waste management stream. Therefore, when an allocation for a cascade recycling is made, the quality or the economic aspect of the recycled material should be considered.

The only way to avoid the allocation for open loop recycling is the expansion of the system under study. This approach requires much work, and it may be impossible to get all relevant data throughout the whole life cycle system, except in a few limited cases. Therefore, a proper allocation method for an open loop recycling system should be established for most cases. Several allocation methods for an open loop recycling have been discussed [1-9]. While most of them do not consider quality degradation, the material pool method [6] and LINDEIJER [7] also take the material quality into account. However, these methods considered only the material quality in the raw material production process, not in the waste management processes of the other life cycle systems. Another possible method that considers the quality is the modified 50:50 method [10].

In this study, an allocation method which considers the **material quality** is proposed. Environmental burdens from the waste management process as well as the raw material production process are allocated to the reference life cycle system by the degree of quality degradation. Environmental burden of the recycling process is also allocated to two life cycle systems involved.

2 Rules for the Proposed Allocation Method

The recycled material can not replace the virgin material for the original use within a given life cycle system because of the quality degradation after use. Furthermore, the quality of the recycled material continues to be degraded

throughout successive life cycle systems and the recycled material is ultimately disposed of. The quality degradation is therefore a main reason for the environmental burdens of the material use and the waste management. Hence, when the environmental burdens from both processes are allocated, the quality of the recycled material should be considered.

2.1 Allocation of the environmental burden due to material use

2.1.1 Responsibility for raw material use

Material is assumed to have an environmental burden [7]. Furthermore, the environmental burden is assumed to be proportional to the material quality. When the life cycle system uses a raw material, whether recycled or virgin, this life cycle system has the responsibility for the environmental burden of the material corresponding to its quality.

Assuming that only recycled material with 60% of the original quality is used in a manufacturing process of a given life cycle system, this life cycle system has the responsibility for 60% of the environmental burden of the virgin material production process. The environmental burdens from the same virgin material production in different life cycle systems are assumed to be the same because the identical process for manufacturing virgin material is used in a given society. In general, unit environmental burden of a manufacturing process taking into account the responsibility for the use of virgin as well as recycled materials in the i^{th} life cycle system, $EB'_{M,i}$, may be expressed as:

$$E'_{M,i} = E_V \cdot (1 - I_i) \cdot Q_{i-1} + E_V \cdot I_i \cdot Q_V \qquad (1)$$

where,

- E_V: Unit environmental burden from the virgin material production process,
- Q_{i-1}: Quality of the recycled material in the i-1^{th} life cycle system,
- Q_V: Virgin material quality (set to 1),
- I_i: Fraction of the virgin material used in the i^{th} life cycle system.

The first term of the equation (1) is the responsibility for using recycled material with the quality Q_{i-1} and the second term is the responsibility for using virgin material in the i^{th} life cycle system. Since the quality of virgin material is set to 1, the equation (1) can be simplified as:

$$E'_{M,i} = E_V \cdot [(1 - I_i) \cdot Q_{i-1} + I_i] \qquad (2)$$

2.1.2 Credit for recycling and using recycled material

Environmental credit due to recycling should be considered because recycling saves virgin material and avoids the use of a waste management system. Environmental credit for saving virgin material is presented here, while environmental credit due to avoiding the use of a waste management system is considered in the part of the allocation of the environmental burden associated with the waste management system.

Since recycling is the mutual need of two life cycle systems, the environmental credit accrued by recycling and the use of recycled material should be evenly distributed to both life cycle systems involved. In this study, the environmental credit is defined as an avoided environmental burden for the virgin material production.

Assume that material with a given quality, say 80% of the original quality after use, goes into the next life cycle system. Since environmental credit should be shared evenly between the two life cycles involved, the previous life cycle system where the material is recycled then gets 40% of the negative environmental burden of the virgin material production process. By the same token, 40% of the negative burdens goes to the next life cycle system where the recycled material is used. Hence, the unit environmental credit accrued by recycling, and use of the recycled material in the i^{th} life cycle system, $EB''_{M,i}$, becomes:

$$EB''_{M,i} = \frac{E_V \cdot [(1 - I_i) \cdot Q_{i-1} + r_i \cdot Q_i]}{2} \qquad (3)$$

where,

r_i: Recycling ratio in the i^{th} life cycle system [0;-1].

Equation (3) consists of two credits. The first is the credit for using the recycled material and the second is the credit for recycling.

2.1.3 Environmental burden for using raw material

From the responsibility [equation(2)] and the credit [equation(3)], the environmental burden due to the use of material, both virgin and recycled, and credit due to recycling in the i^{th} life cycle system, $EB_{M,i}$, may be expressed as:

$$\begin{aligned} EB_{M,i} &= EB'_{M,i} - EB''_{M,i} \\ &= E_V \cdot [(1 - I_i) \cdot Q_{i-1} + I_i] - \frac{E_V \cdot [(1 - I_i) \cdot Q_{i-1} + r_i \cdot Q_i]}{2} \\ &= \frac{E_V \cdot [(1 - I_i) \cdot Q_{i-1} - r_i \cdot Q_i]}{2} + E_V \cdot I_i \end{aligned} \qquad (4)$$

2.2 Allocation of the environmental burden from the recycling process

Since recycling takes place as a result of material needs between the two life cycle systems involved, the environmental burdens from the recycling process are assumed to be distributed evenly between two adjacent life cycle systems.

This assumption is adopted from the 50:50 allocation method. The unit environmental burden from the recycling process allocated to the i^{th} life cycle system, $EB_{R,i}$, is:

$$EB_{R,i} = \frac{(1-l_i)\cdot R_{i-1} + r_i \cdot R_i}{2} \tag{5}$$

where,

R_i: Unit environmental burden from the recycling process in the i^{th} life cycle system.

2.3 Allocation of the environmental burden from the waste management system

There are two aspects associated with the environmental burden of the waste management system.

1. One aspect is the disposal of the material within a given life cycle system itself.
2. Another is the disposal of the material in other life cycle systems.

First, the environmental burden due to disposal within a given life cycle system is considered.

The life cycle system where material is disposed of has the responsibility of the environmental burden of the waste management process because disposal eliminates the opportunity for further recycling. The environmental burden from the waste management process is assumed to be allocated in proportion to the quality of the material disposed of. Therefore, the unit environmental burden due to disposal of material in the i^{th} life cycle system, W_i', may be expressed as:

$$W_i' = W_i \cdot (1-r_i)\cdot Q_i' \tag{6}$$

where,

W_i: Unit environmental burdens from the waste management process in the i^{th} life cycle system,

Q_i': Quality of the material used in the i^{th} life cycle system,

$[= (1-l_i)\cdot Q_{i-1} + l_i \cdot Q_v = (1-l_i)\cdot Q_{i-1} + l_i]$.

Equation (6) shows environmental burden caused by the disposal of the material in the i^{th} life cycle system. This equation also takes into account the environmental credit due to recycling for avoiding use of the waste management system implicitly. Environmental burdens caused by disposal of the material in other life cycle systems, however, should also be taken into account because one of the reasons for the disposal of the material is its quality degradation. The life cycle system where the quality degradation occurs should be responsible for the environmental burdens from the waste management processes in other life cycle systems. Therefore, those unit environmental burdens allocated to the i^{th} life cycle system due to waste management processes in other life cycle systems, W_i'', are:

$$W_i'' = (Q_i' - Q_{i+1})\cdot \sum_{j=i+1}^{f}(1-r_j)\cdot W_j \cdot \prod_{k=i}^{j-1} r_k \tag{7}$$

where

f: The last life cycle system.

Equation (7) requires all information on other life cycle systems such as recycling ratios and unit environmental burdens of the waste management processes. In practice, it is nearly impossible to collect all specific data. However, the waste management process for the same material, which consists of the same chemical composition, is assumed to be the same within a given society. Therefore, equation (7) may be simplified as:

$$W_i'' = W_g \cdot r_i \cdot (Q_i' - Q_{i+1}) \tag{8}$$

where,

W_g: Unit environmental burden from the general waste management system.

Therefore, the allocated environmental burden from the waste management process to the i^{th} life cycle system, $EB_{w,i}$, becomes:

$$\begin{aligned} EB_{w,i} &= W_i' + W_i'' \\ &= W_g \cdot r_i \cdot (Q_i' - Q_{i+1}) + W_g \cdot (1-r_i)\cdot Q_i' \\ &= W_g \cdot (Q_i' - r_i \cdot Q_{i+1}) \end{aligned} \tag{9}$$

In equation (9), it is not necessary to know the waste management processes for all life cycle systems. Only the information on the general waste management system for the material under consideration is required.

2.5 Environmental burden in the i^{th} life cycle

From the above equations, the unit environmental burdens in the i^{th} life cycle system, EB_i, can be obtained as:

$$\begin{aligned} EB_i &= EB_{M,i} + EB_{P,i} + EB_{U,i} + EB_{R,i} + EB_{W,i} \\ &= \frac{E_v \cdot [(1-l_i)\cdot Q_{i-1} - Q_i \cdot r_i]}{2} + E_v \cdot l_i + \frac{(1-l_i)\cdot R_{i-1} + r_i \cdot R_i}{2} \\ &\quad + W_g \cdot (Q_i' - r_i \cdot Q_{i+1}) + EB_{P,i} + EB_{U,i} \end{aligned} \tag{10}$$

where,

$EB_{P,i}$: Unit environmental burdens from the product manufacturing phase in the i^{th} life cycle system,

$EB_{U,i}$: Unit environmental burdens from the use phase in the i^{th} life cycle system.

The environmental burdens caused by transportation are included in each phase. This method does not require additional information on other life cycle systems in order to allocate environmental burdens. Only the information from recycling processes before and after the life cycle system needs to be collected.

3 Results and Discussion

To show how this method works, a fictitious system is adopted. The system is assumed to be composed of three life cycle systems.

1. The first life cycle system uses only a virgin material and the quality of the virgin material is set to 1.0. The recycling ratio and the quality of the recycled material from the first recycling process is assumed to be 75% and 0.8, respectively.
2. In the second life cycle system, the material used consists of 75% of the recycled material and 25% of the virgin material. The recycling ratio and the quality of the recycled material after the second recycling process is assumed to be 75% and 0.6, respectively.
3. In the last life cycle system, the material used consists of 75% of the recycled material from the second life cycle system and 25% of the virgin material. All materials are disposed of after use.

The process tree for three life cycle systems is shown in **Figure 1**. For the purpose of illustration, it is also assumed that there are no environmental burdens from the product manufacturing phase and the use phase.

The allocated environmental burdens for each life cycle are shown in **Figure 2**. The negative environmental burden is caused by an environmental credit from recycling or using recycled material corresponding to its quality

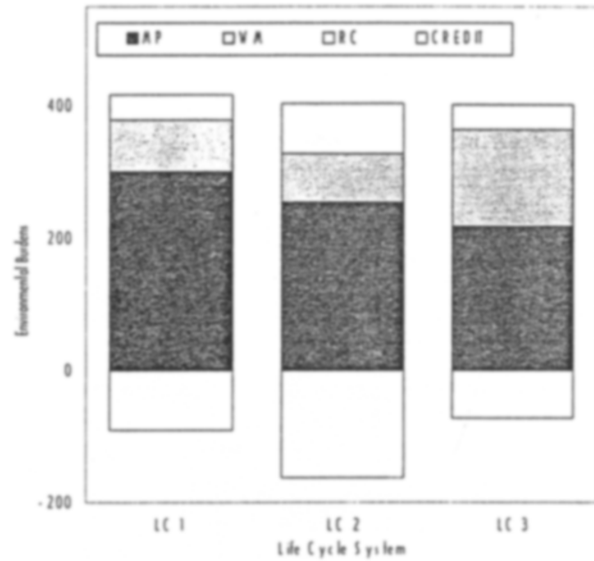

Fig. 2: Environmental burdens in each life cycle. The material quality after the first life cycle system becomes 0.8 of the original quality and the quality after the second life cycle system is 0.6 of the original quality. **MP:** Environmental burden due to using the virgin material. **WM:** Environmental burden from the waste management process. **RC:** Environmental burden from the recycling process. **Credit:** Environmental credit for recycling and using the recycled material

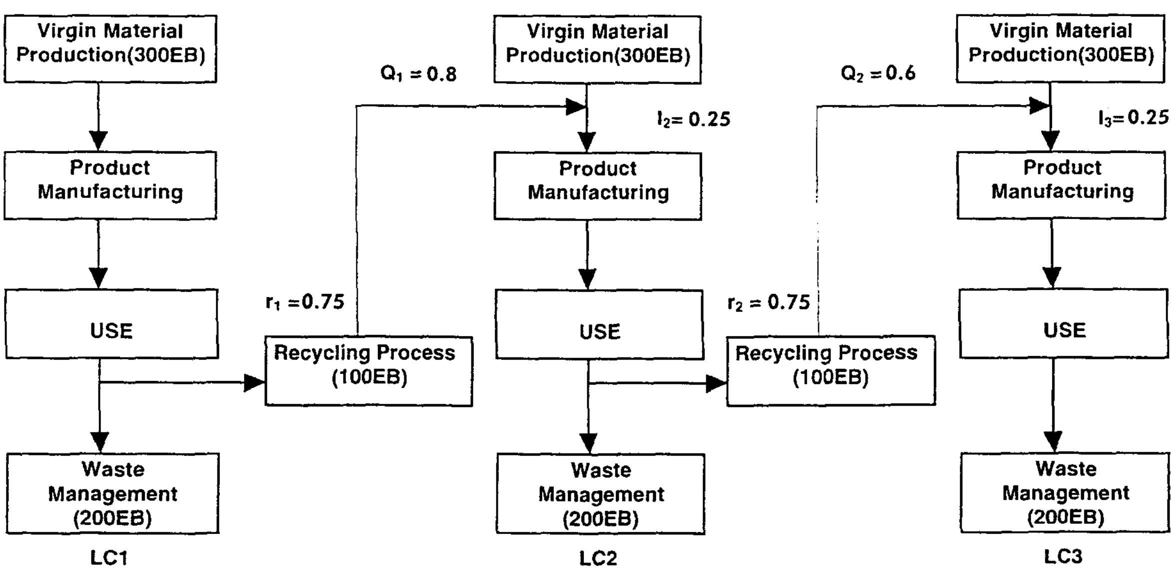

Fig. 1: Process tree for three life cycle systems. EB is the environmental burdens per one kg. It is assumed that there are no environmental burdens from the product manufacturing process phase and the use phase

Since there is no recycled material used in the *first life cycle system*, the **environmental burden** from the **material use** is the highest. The **credit for recycling** in the *second life cycle system* is the highest because this life cycle system uses the recycled material and recycles the material after use. However, the environmental burden caused by the recycling process in the second life cycle system is twice as high as that in the other two life cycle systems. This is because recycling occurs as a mutual need between the two life cycle systems. The **environmental burden** from the **waste management** in the *third life cycle system* is the highest because of the disposal of all materials without recycling.

Figure 3 shows the environmental burdens when the quality of the recycled material from the second life cycle system changes from 0.6 to 0.3. The total environmental burden in the second life cycle system increases because of the significant drop in quality of the recycled material. The greater the degradation of the recycled material quality, the larger environmental burden.

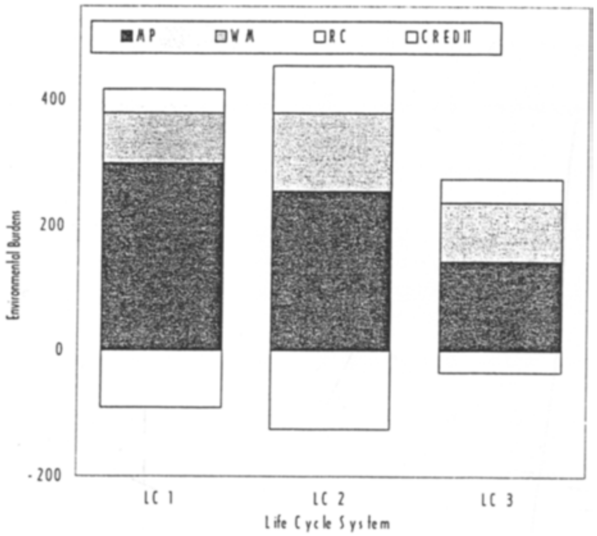

Fig. 3: Environmental burdens in each life cycle. The material quality after the first life cycle system becomes 0.8 of the original quality and the quality after the second life cycle system is 0.3 of the original quality. **MP:** Environmental burden due to using the virgin material. **WM:** Environmental burden from the waste management process. **RC:** Environmental burden from the recycling process. **Credit:** Environmental credit for recycling and using the recycled material

The material pool method and 50:50 method are also chosen to compare the difference between allocation methods. The material pool method introduces the concept of material pools where material is delivered for the recycling. The delivery of material to the material pool is considered as an environmental credit which corresponds to its quality. Furthermore, the use of recycled material causes an environmental burden depending on its quality [4]. The 50:50 method allocates 50% of environmental burdens from the virgin material production and waste management in proportion to the amount of virgin material in the product and remaining 50% in proportion to the amount of material lost from the technosphere to the environment. Environmental burden from the recycling process is allocated evenly between two adjacent life cycle systems [1].

There are several allocation methods for an open loop recycling system, but most methods do not consider the material quality except the material pool method It is sufficient to chose the 50:50 method as well as the material pool method among others to elucidate the difference in considering the material quality. **Figure 4** shows the comparison results in each life cycle system.

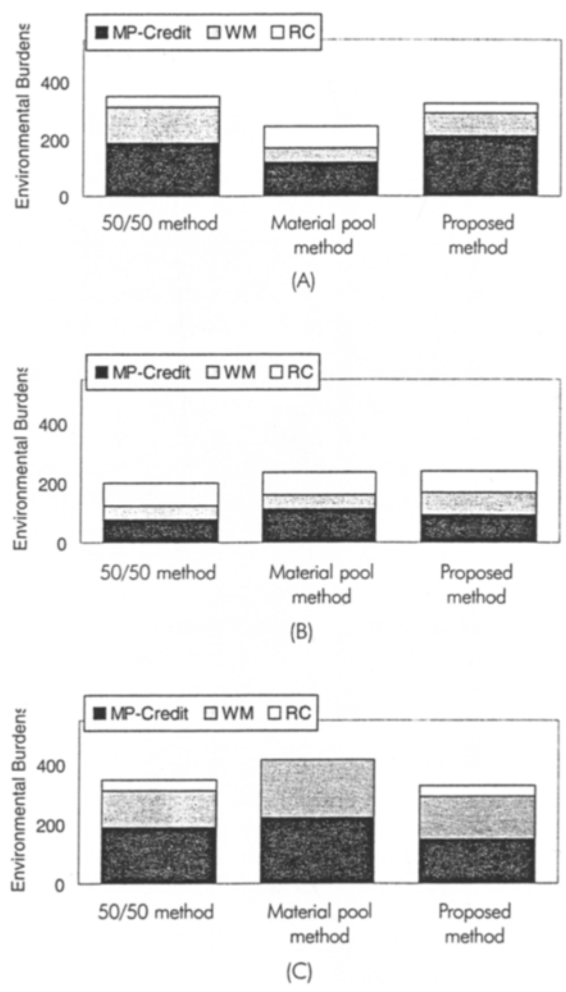

Fig. 4: Comparison of different allocation methods.
(A) The first life cycle system; (B) The second life cycle system; (C) The third life cycle system.
The material quality after the first life cycle system becomes 0.8 of the original quality and the quality after the second life cycle system is 0.6 of the original quality. **MP-Credit:** Environmental burden of the virgin material use minus credit for recycling and use of the recycled material. **WM:** Environmental burden from the waste management process. **RC:** Environmental burden from the recycling process

1. In the first life cycle system, the environmental burden from the waste management process in the 50:50 method is the highest because environmental burdens for the material use and the waste management are equally distributed to the first cycle system and the last life cycle system without consideration of the material quality. The reason for the higher environmental burden of the waste management process in the proposed method over the material pool method in the first life cycle system is that the proposed method considers the environmental burdens of the disposal in other life cycle systems due to degradation of the material quality, while the material pool method does not. The environmental burden for recycling in the material pool method are not allocated because the recycling process is assumed to be included within the system boundary. In the proposed method, the material quality is reduced by 20% after the first life cycle system and the responsibility for the quality degradation resides in the first life cycle. Thus, the environmental burden from the material use in the proposed method is greater than that with the other methods.
2. The same concept is applied to the second and last life cycle systems. According to the concept of the material pool method, the life cycle system with the disposal of material has the responsibility for the environmental burden of the material manufacturing process corresponding to the amount of the disposed material. This is why the material pool method has the highest environmental burden in the material use which takes into account the environmental burdens of the material manufacturing process in the last life cycle system. In the proposed method, the environmental burden of the material use and from the waste management take into account the quality as well as the quantity of material.

The application of the proposed allocation method requires a quality indicator of the material. LINDEIJER [7] discussed the fact that a quality indicator should be based on a socio-economic value or physical property. Both values have their own problems in the application. It is difficult to define unique physical property as a quality indicator because there are lots of properties related to the material quality. The economic value is often unstable and affected by economic and social situations. However, the demand for a certain quality of material also depends on its economic value; thus, the economic value is recommended for the quality indicator for most cases even though its value is fluctuating. Clearly, it is desirable that several quality indicators should be used in order to reduce the uncertainty. More work is required to develop reliable quality indicators.

4 Conclusions

In this study, the allocation method for the cascade recycling system is developed that considers both the quality and quantity of material.

- The life cycle system in which raw material is used should have the responsibility for the material use corresponding to its quality. The environmental burdens of the virgin material production are allocated to the related life cycle systems in proportion to the material quality.
- The credit accrued by recycling and using recycled material should be considered in connection with the material quality. The environmental credit defined as an avoided environmental burden for the virgin material production is allocated equally to the life cycle systems involved.
- One of the main reasons for the disposal of material is its quality degradation. Therefore, the degradation of the material quality should be considered. The environmental burdens of the waste management system in other life cycle systems, as well as in a given life cycle system, are allocated to the life cycle system under consideration in a proper share corresponding to the material quality.

Regarding the application of the proposed method, the only data required includes data for the life cycle system under study and the information on the recycling process, provided that the same virgin material is used within the whole life cycle systems. The choice of the quality indicator as well as the allocation method depends on the goal of an LCA study. These choices influence the results of the LCA study. To reduce the uncertainty, the sensitivity of the quality indicator and the allocation method should be investigated in a sensitivity analysis.

5 References

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